12 December 1980, Volume 210, Number 4475

SCIENCE

Intermediate Bosons: Weak Interaction Couriers

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Summary. Recent progress toward a complete theory of the weak interactions has led to sharper predictions for the properties of the hypothetical weak-force particles known as intermediate bosons. The history of speculations about intermediate bosons is briefly summarized and the (as yet negative) searches carried out for these particles are reviewed. Prospects for future searches—both direct and indirect—are surveyed, and the consequences of finding the expected or unexpected are noted.

The time is almost ripe, most elementary-particle physicists would agree, to install the current unified theory of weak and electromagnetic interactions (*1*) in basic physics textbooks. What lies behind our hesitation, in the face of the striking experimental successes of the theory? It is that the agents of the weak interaction called intermediate bosons, the particles whose existence is implied by the unification of the apparently distinct weak and electromagnetic interactions, have not yet been found. At present, intensive experimental searches (many involving audacious new ideas for the use of particle accelerators) are being mounted to look for such objects with the properties predicted by the theory. Our purpose here is to explain the theoretical significance of the intermediate bosons and to describe past and future searches for these particles.

The contemporary view of the elusive weak-force particles is the result of a long evolution of the theory of the weak interactions, the most familiar manifestation of which is the radioactive β-decay of nuclei. The first step toward a quantitative description of β-decay was taken in 1933, when Fermi wrote down what is now called the four-fermion interaction (*2*). According to this picture, the decay of a neutron into a proton is accompanied by the emission of an electron (the "β-ray") and an antineutrino (*3*). The Fermi theory was conceived in analogy with quantum electrodynamics (QED), the theory which governs the interaction of electromagnetic radiation with matter. The electron-antineutrino pair was to play a role analogous to that played by the photon in electromagnetic transitions. Like the emission of a photon, the β-decay transition takes place in Fermi's theory at a single space-time point.

Unlike the emitted photon, which has a definite (zero) mass, the electron-antineutrino pair is a composite system whose effective mass may vary from one process to another. Thus the analogy is incomplete: the photon emitted in radiative transitions is the force particle of QED, but the electron-antineutrino composite is apparently not the force particle of the weak interactions. Nuclear β-decay is the first example of what is now known as a charged current interaction: a process which changes the charge of the interacting particle by one unit. In our example, the electrically neutral neutron is changed into a positively charged proton. The change in charge is compensated by the emission of the negatively charged electron-antineutrino pair. Before going on, we may emphasize that with a single crucial modification, Fermi's theory remains an essentially correct description of charged current processes at low energies.

The Idea of Intermediate Bosons

It was against this background that the intermediate boson hypothesis came into focus. For a brief period in the 1930's, it seemed natural to seek a unified explanation of the two newly discovered nuclear forces: the strong force which binds protons and neutrons in the nucleus and the weak force responsible for β-decay. In his classic 1935 paper on nuclear forces, Yukawa (*4*) introduced a revolutionary idea. He postulated the existence of a spinless elementary particle, later called the meson, the exchange of which gave rise to the attractive short-range interaction between neutron and proton (*5*). To account for the observed range of nuclear forces, Yukawa's meson was required to have a mass about 200 times the electron mass. Yukawa further speculated that the meson could also be the carrier of the weak force responsible for β-decay. This line of reasoning correctly anticipates the decay of the meson (for example, $\pi \rightarrow e\bar{\nu}_e$ where e is an electron and $\bar{\nu}_e$ is an electron antineutrino), but deviates from the Fermi theory, in which the spin of the electron-neutrino complex is one, not zero. It also fails to account for the very different strengths of the two interactions. A unified description of the strong and weak interactions was not to be found.

What appears to be the first suggestion of an intermediate vector boson (IVB), that is, a spin-one particle, was expounded in a little-known article by Klein in 1938 (*6*). Klein constructed a model in which massive charged vector particles (denoted W) mediated β-decay. In this model, Fermi's analogy between β-decay and radiative processes was

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0036-8075/80/1212-1205$01.75/0

made closer; the intermediate boson was assumed to couple with electromagnetic strength to the neutron-proton and neutrino-electron pairs. In such a picture the weak interaction is no longer of zero range, but is characterized by a range $r_0 = \hbar/M_W c$, where $2\pi\hbar$ is Planck's constant, M_W is the mass of the weak boson, and c is the speed of light. The contrast is illustrated in Fig. 1. Thus a large intermediate boson mass is suggested by the short range of the β-decay interaction. It is also required by the feeble strength of β-decay processes. Identifying Klein's description of β-decay with Fermi's gives $M_W^2 = 4\pi\alpha\sqrt{2}/G_F \approx (100\ \mathrm{GeV}/c^2)^2$, where $\alpha \approx 1/137$ is the fine structure constant and $G_F = 1.16 \times 10^{-5}\ \mathrm{GeV}^{-2}$ is the Fermi coupling constant. The intermediate boson mass is the only free parameter in Klein's model. More than 30 years were to pass before theory could predict that parameter. The ability to do so is intimately tied to the unification of weak and electromagnetic interactions presaged in Klein's work.

Before sketching the elements of present-day unified theories, let us continue our chronology. A crucial development was the discovery in 1956 by Lee and Yang (*7*) of the possibility that parity invariance could be violated in the weak interactions. They noted that invariance of the weak interactions under reflection symmetry was an implicit assumption without underlying experimental support, and proposed a series of experimental tests. The hypothesis of parity violation was spectacularly confirmed in a series of elegant experiments (*8*). Feynman and Gell-Mann, Sudarshan and Marshak, and Sakurai (*9*) thereupon generalized Fermi's vector theory of β-decay into the V − A (vector minus axial vector) theory. The extension of this interaction to other weak processes is readily accomplished. The V − A theory was a stunning phenomenological success, predicting many detailed features of weak interactions such as muon decay $\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$, where ν_μ is the muon neutrino. Even today it accounts for all the observed features of charged-current interactions (*10*).

Like the original Fermi theory, the V − A theory is a prescription for an effective interaction at low energies. The zero-range or point-coupling description conflicts with the conservation of probability at high energies, however. For example, the cross section for the reaction $\nu_\mu e \rightarrow \mu\nu_e$ is predicted in lowest order to grow as the square of the center of mass (CM) energy, but unitarity provides an upper bound that decreases as the inverse square of the CM energy. The prediction and the bound conflict for CM energies exceeding 600 GeV. The divergence of the point-coupling theory grows more severe in each order of perturbation theory. Therefore, as is well known, major revision is required to obtain a satisfactory theory.

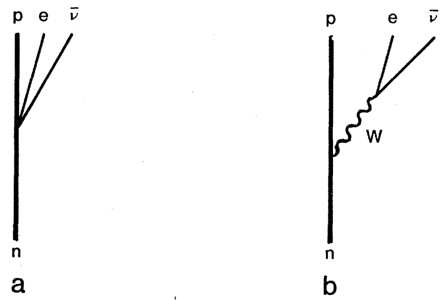

Fig. 1. (a) Neutron decay according to the point-coupling picture of Fermi. (b) Intermediate boson interpretation of neutron decay.

A natural first step is to attempt to arrange a constant cross section at high energies by assuming, in analogy with QED, that the weak interaction is mediated by exchange of a spin-one boson. Historically (*11*), three properties have been imputed to the intermediate boson W:

1) It carries charge ±1, because the familiar manifestations of the weak interaction (such as β-decay) are charge-changing.

2) It must be rather massive, to reproduce the short range of the weak force.

3) Its parity is indefinite.

Furthermore, its couplings to other particles are fixed by the low-energy phenomenology. Some problems remain. The lowest order prediction violates unitarity at exponentially high energies, and higher order contributions are incalculable because the theory is not renormalizable.

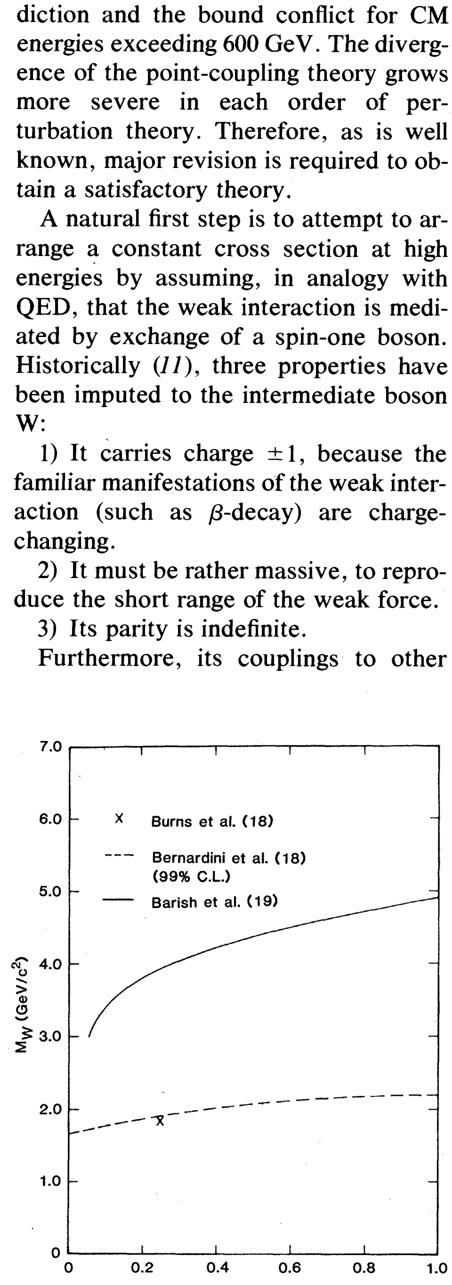

Fig. 2. (Solid curve) Lower limit [90 percent confidence limit (C.L.)] on the W boson mass set by the neutrino experiment of Barish *et al.* (*19*), as a function of the leptonic branching ratio. Limits from earlier neutrino experiments are also shown.

Although the intermediate boson theory is therefore incomplete in this form, it represents a considerable improvement over the point-coupling picture. The next decade saw many unsuccessful attempts to make a satisfactory theory, which we need not review here. Even in the absence of a complete theory, the intermediate boson hypothesis was sufficiently definite to predict the properties of the intermediate bosons with some confidence, and sufficiently plausible to inspire experimental searches.

In an early paper (*12*), Lee and Yang considered the consequences of intermediate bosons for muon decay. Their analysis showed that the existing data on the electron energy spectrum could tolerate an intermediate vector boson mass as small as about 1 GeV/c^2. The mass of the intermediate boson was not specified by the theory, but speculations along the lines of Klein's ideas about the equality of the photon and intermediate boson couplings led to the suggestion (*13*) that $M_W \approx 60$ times the proton mass. Because the W can decay into $e\bar{\nu}_e$ and so on, it will be an unstable particle. The decay rate is fixed by the low-energy phenomenology as

$$\Gamma(W \rightarrow e\bar{\nu}_e) = G_F M_W^3/6\pi\sqrt{2}$$

$$\simeq 6.64 \times 10^{17}\left(\frac{M_W}{1\ \mathrm{GeV}/c^2}\right)^3 \mathrm{sec}^{-1}$$

The intermediate boson can also decay into $\mu\bar{\nu}_\mu$ and into strongly interacting particles. If $B(W \rightarrow e\bar{\nu}_e) < 1$ represents the fraction of decays into electron and neutrino, the lifetime of the intermediate boson will be

$$\tau_W = B(W \rightarrow e\bar{\nu}_e)\hbar/\Gamma(W \rightarrow e\bar{\nu}_e)$$

$$\lesssim 1.5 \times 10^{-18}\left(\frac{1\ \mathrm{GeV}/c^2}{M_W}\right)^3 \mathrm{sec}$$

which makes it very unstable indeed.

Early Searches

In the early 1960's, it was noticed by Schwartz and by Pontecorvo (*14*) that high-energy neutrino beams could be produced with secondary beams from proton accelerators. The prospect of these new tools stimulated intensive study of the weak interactions (*15*). The first major undertaking was the demonstration (16) at Brookhaven National Laboratory and at the European Organization for Nuclear Research (CERN) of the absence of the reaction $\nu_\mu n \rightarrow e^- p$ (n and p are a neutron and a proton), which proves that the electron neutrino and the muon neutrino are distinct. At once the experimental groups addressed the question of direct production of intermediate bosons by the dissociation of $\nu_\mu \rightarrow W^+\mu^-$ in the Coulomb field of a nucleus. It is straightforward to estimate the production cross section (17), and the leptonic decays $W^+ \rightarrow e^+$ (ν_e undetected) or μ^+ (ν_μ undetected) provide characteristic signatures. The early counter and bubble chamber experiments provide no evidence for dilepton events characteristic of IVB production and decay. This led to the conclusion (18) that $M_W \gtrsim 2$ GeV/c^2. Subsequent experiments (19) at higher energies have implied stricter lower limits on M_W, which are summarized in Fig. 2.

An indirect manifestation of intermediate bosons in neutrino physics would be the observation of deviations from the linear energy dependence predicted in the point-coupling theory for the total cross section of neutrinos on structureless particles. Experiments to measure the scattering of high-energy electrons and muons from nucleons have established that, to a good approximation, protons and neutrons behave as collections of structureless objects, which have been identified as quarks (20). Therefore we may expect that, in the point-coupling limit of infinitely massive (which is to say no) intermediate bosons, the total cross section for neutrino-nucleon (νN) scattering is

$$\sigma(\nu N) \propto G_F{}^2 M E_\nu$$

where M is the nucleon mass and E_ν is the neutrino energy. In the IVB picture, in contrast, the intermediate boson propagator serves to damp the cross section, and one expects

$$\sigma_{IVB}(\nu N) \propto G_F{}^2 M_W{}^2 \log\left(1 + \frac{2ME_\nu}{M_W{}^2}\right)$$

The two expressions coincide when $M_W{}^2 >> 2ME_\nu$, but the IVB theory predicts that the cross section will begin to fall below a linear extrapolation at neutrino energies $E_\nu \gtrsim M_W{}^2/2M$. No significant departures from linear behavior have yet been observed (21). Early experiments that sought to identify cosmic-neutrino-induced interactions deep underground placed lower limits of several GeV/c^2 on M_W (22). Subsequent precise measurements of the neutrino total cross sections at high-energy accelerators (23) are summarized in Fig. 3. They imply $M_W \gtrsim 30$ GeV/c^2.

A third traditional technique for intermediate boson searches has been to exploit the expectation that the decay of a heavy W produced in collisions of strongly interacting particles would impart a large transverse momentum (as much as $M_W/2$) to the muon (or electron) in the decay $W \rightarrow e\nu$ or $\mu\nu$. Although it had been recognized quite early that IVB's might be produced in hadron-hadron collisions (24), estimates of the production cross section were uncertain by several orders of magnitude. In addition, the leptonic branching ratio was not reliably calculable. Consequently, a negative search would be difficult to interpret. However, the higher primary energies available for proton beams as opposed to neutrino beams promised to extend the range of kinematically accessible masses. The first such experiments, carried out in 1965, searched for IVB's in 12, 20, and 30 GeV/c proton-nucleon collisons (25). No hint of muons with large transverse momentum was found, above the level of unavoidable backgrounds. It was swiftly pointed out by Okun and by Yamaguchi (26) that the celebrated conserved vector current (CVC) hypothesis relating β-decay and radiative transition rates (27) implied a connection between the rates for production of intermediate bosons and of massive (virtual) photons, which could decay into muon pairs.

This observation made it plain that it would not be enough to detect muons with high transverse momentum; to establish that the signal came from W decay, the absence of a second muon would have to be demonstrated. Thus was born the study of dilepton production in collisions of strongly interacting particles (28), an experimental enterprise which has uncovered the existence of the J/ψ and upsilon families of heavy particles as well as a smooth continuum of massive lepton pairs. Having found the virtual-photon continuum, we may now invert the CVC argument to predict the cross section for W production with new confidence. No indication of the production and decay of the W has yet been observed (29).

Unifying Fundamental Interactions

At the base of the unification of interactions is the idea of gauge invariance, which draws its name from some early

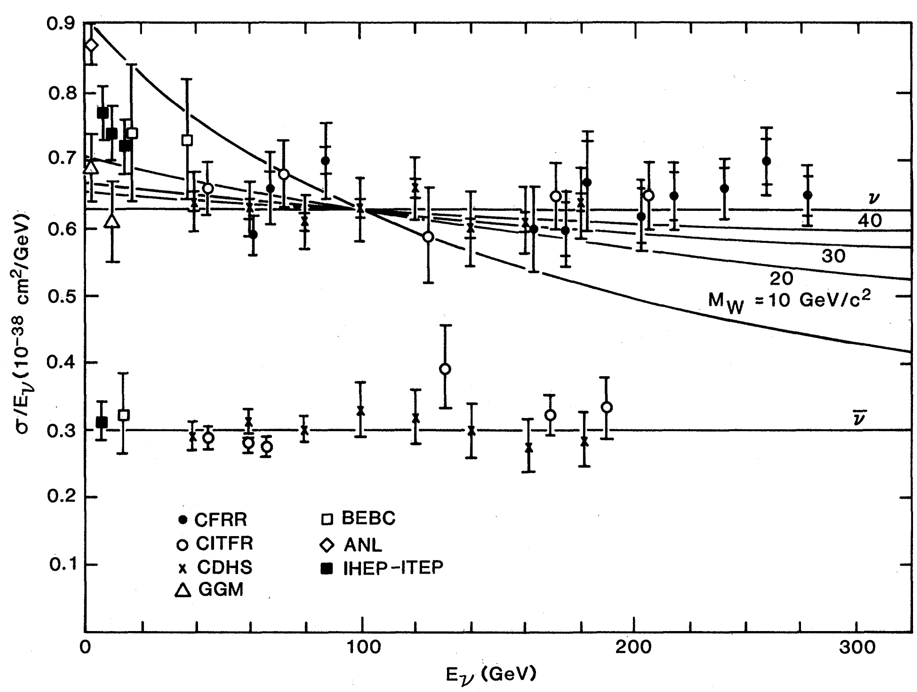

Fig. 3. High-energy measurements of neutrino-nucleon total cross sections divided by the incident neutrino energy [from (23)]. The horizontal lines denote best-fit values $\sigma(\nu N)/E_\nu = 0.63 \pm 0.02$ and $\sigma(\bar{\nu}N)/E_\nu = 0.30 \pm 0.01$. The remaining curves illustrate the effects on νN scattering of intermediate bosons with masses M_W = 10, 20, 30, and 40 GeV/c^2, arbitrarily normalized to the 100-GeV datum. Data are from the Caltech-Fermilab-Rochester-Rockefeller Collaboration (*CFRR*); the Caltech-Fermilab-Rockefeller Collaboration (*CITFR*); the CERN-Dortmund-Heidelberg-Saclay Collaboration (*CDHS*); the Gargamelle Bubble Chamber Collaboration (*GGM*); the Big European Bubble Chamber Collaboration (*BEBC*); the Argonne National Laboratory 12′ Bubble Chamber Collaboration (*ANL*); and the Institute for High Energy Physics, Serpukhov-Institute for Theoretical and Experimental Physics, Moscow, Collaboration (*IHEP-ITEP*).

investigations by Weyl (*30*) into a possible connection between scale changes and the laws of electromagnetism. Weyl's specific attempt to deduce electromagnetism from a symmetry principle—invariance under a change of length scale at every position of space-time independently—ran afoul of quantum mechanics, but the general strategy and the name have survived. Indeed, gauge theories constructed to embody various symmetry principles are now believed to provide the correct quantum descriptions of the strong, weak, and electromagnetic interactions.

The simplest example of a gauge theory is electromagnetism itself. How does it follow from a symmetry principle? Quantum mechanical observables do not depend on the phase of the complex wave function which describes the state of a system. Therefore, one has the freedom to rotate the phase of a wave function by an amount which is the same at all times and places without affecting the physical consequences of the theory. The choice of phase is thus conventional, as opposed to observable. This is known as a global symmetry principle. It is natural to ask whether it should not be possible to choose this arbitrary convention independently at each point of space-time, again without affecting the physical consequences of the theory. It is, in fact, possible to construct a quantum theory which is invariant under local (that is, position- and time-dependent) phase rotations that are proportional to the electric charge of the particles, but only if the theory contains an electromagnetic field with precisely the properties summarized by Maxwell's equations. In the quantum theory, a massless vector particle identified as the photon mediates the electromagnetic interaction. The interactions of matter with electromagnetism are essentially specified by the requirement of local phase invariance.

Local phase rotations of the kind described above are the simplest examples of local gauge transformations. For a continuous symmetry, global gauge invariance implies the existence of a set of conserved currents. In the case of electromagnetism, the electric current is conserved. A local gauge invariance requires, in addition, the existence of massless gauge fields. The photon is the gauge field of electromagnetism. The set of phase transformations forms the one-parameter group U(1). The local gauge invariance of electromagnetism was discovered more than 60 years after the theory had been codified by Maxwell. However, it frequently happens in physics that the symmetries respected by a phenomenon are recognized before a complete theory has been developed. Could the notion of local gauge invariance be used to deduce the theory?

This question was addressed in 1954 by Yang and Mills and independently in 1955 by Shaw (*31*). Early in the study of nuclear forces it was established that the nuclear interaction is charge-independent; it acts with the same strength between proton and proton, or proton and neutron, or neutron and neutron. This may be understood by saying that the proton and neutron represent two states of the same particle, the nucleon. Just as an electron can be in a state with spin up or spin down, a nucleon can be in a state with the internal quantum number isospin up (defined as the proton), or isospin down (defined as the neutron). Charge independence then would reflect the invariance of the strong interactions under isospin rotations, characterized by the group SU(2). If isospin is regarded as a gauge group, local gauge invariance requires the existence of three massless vector gauge particles, corresponding to the three generators of SU(2). The interactions of the gauge particles with nucleons are prescribed by the gauge principle. All of this is entirely parallel to the theory of electromagnetism. What distinguishes this SU(2) gauge theory from its U(1) counterpart is that the SU(2) gauge fields carry isospin and thus couple among themselves, whereas the photon (being electrically neutral) is not self-interacting. Interacting gauge fields are an attribute of any theory based on a non-Abelian gauge group. Its elegant mathematical properties notwithstanding, the Yang-Mills theory was unacceptable as a description of nuclear forces because they are not mediated by massless particles. The masslessness of the gauge particles is a feature required by gauge invariance.

Very similar reasoning has interesting consequences for a theory of weak interactions. It is appealing to regard the proton and neutron, the electron and its neutrino, and the muon and its neutrino as doublets

$$\mathrm{N} \equiv \begin{pmatrix} \mathrm{p} \\ \mathrm{n} \end{pmatrix},\ \mathrm{E} \equiv \begin{pmatrix} \nu_e \\ \mathrm{e} \end{pmatrix},\ \mathrm{M} = \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

under a "weak-interaction isospin" symmetry (*32*), since the weak interactions involve transformations $p \leftrightarrow n$, $\nu_e \leftrightarrow e$, $\nu_\mu \leftrightarrow \mu$, and so on. Local gauge invariance under weak isospin transformations then implies the existence of three massless gauge bosons, W^+, W^-, and W^0. Because the gauge symmetry is imposed on all three weak doublets, the vector bosons couple universally, with a unique coupling constant, to N, E, and M. The universal strength of weak interactions is a key experimental fact. That it arises naturally from a gauge theory is noteworthy. Unfortunately, this scheme for the weak interactions has the same shortcoming as the Yang-Mills proposal for strong interaction isospin: the gauge bosons in the theory are massless, but the short-range weak forces in nature must be mediated by heavy particles. The gauge bosons can acquire masses only if the local gauge symmetry is broken in some manner.

In 1957, Schwinger (*33*) first proposed a model of unified weak and electromagnetic interactions based on the global internal symmetry group O(3), which is essentially equivalent to SU(2). There are three vector bosons, W^+, W^-, and W^0, transforming as a three-component vector under the isospin group O(3). The two charged vector bosons are identified as the agents of the weak interaction, and the neutral boson W^0 is identified with the photon. Being partners of the photon, the charged vector bosons W^+ and W^- are expected to interact universally with the electric charge, which implies the equality of the weak and electromagnetic couplings, much as Klein had speculated long before. For this theory to describe reality, it is necessary that the weak bosons acquire masses while the photon remains massless. Schwinger achieved this by postulating couplings of the vector bosons to auxiliary scalar and pseudoscalar fields. Although this procedure does not entail a specific prediction for the mass of the intermediate boson, it anticipates the Higgs mechanism, which is central to current understanding of masses. Schwinger's model was proposed before the $V - A$ structure of the charged weak current was established, and does not yield a $V - A$ form for the interaction. It is nevertheless a prototype for gauge theories of the weak and electromagnetic interactions.

The first attempt to incorporate the $V - A$ structure into a gauge theory of weak interactions was made by Bludman (*34*) in 1958. This model was also based on the weak isospin gauge group SU(2), which requires three massless gauge bosons, W^+, W^-, and W^0. As in Schwinger's model, the masses of the intermediate bosons are contrived in an ad hoc fashion and consequently are not predicted. In contrast to Schwinger's model, in which W^0 is identified as the photon and does not acquire mass, the neutral gauge boson is massive and mediates a (then undiscovered) parity-violating weak interaction. Furthermore, no attempt is made to unify weak and electromagnetic interactions, with their different space-time properties. The so-called neutral current interaction would mediate reactions such as $\nu_e p \rightarrow \nu_e p$, in which the charge of the participating particles does not change. Neutral current interactions were not established experimentally until 1973 (*35*). It is now known that they do not have the pure V − A structure of Bludman's model.

A key insight came with the recognition that the weak and electromagnetic interactions admit a larger gauge symmetry than the isospin group. An important tool for the classification of strongly interacting particles is the Gell-Mann–Nishijima formula (*36*) for displaced charge multiplets

$$Q = I_3 + Y/2$$

which relates the electric charge (Q) to the third component of isospin (I_3) and an additive quantum number called hypercharge (Y). Application of this formula to the weak doublets N, E, and M leads to the hypercharge assignments $Y(\mathrm{N}) = 1$ and $Y(\mathrm{E}) = Y(\mathrm{M}) = -1$. If the hypercharge is associated with a one-parameter group of phase rotations U(1), it appears natural to require that the weak and electromagnetic interactions be invariant under the combined gauge group $SU(2) \otimes U(1)$ of isospin plus hypercharge rotations. Imposition of local gauge invariance now requires the existence of four massless gauge bosons. As before, the W^+, W^-, and W^0 correspond to the generators of weak isospin and have interactions which are characterized by a common coupling strength g. In addition, the neutral gauge boson B^0 associated with the hypercharge symmetry will interact with the fermions with a different coupling strength g'. This kind of a model was formulated by Glashow (*37*) in 1961, following Schwinger's and Bludman's examples.

The Gell-Mann–Nishijima formula suggests that the physical photon, which is coupled to electric charge, must be a linear combination of the gauge particles W^0 and B^0 associated with I_3 and Y, respectively. In addition to the intermediate bosons W^+ and W^- corresponding to the charged current interaction, there remains the orthogonal combination of W^0 and B^0, designated Z^0. It is possible, as discussed previously, to introduce masses by hand in such a manner that $W^\pm$ acquire a mass M_W, Z^0 acquires a mass M_Z, and the photon remains massless, as a consequence of electromagnetic gauge invariance. But this procedure explicitly breaks the original gauge invariance of the interaction Lagrangian. Is it possible to preserve the gauge invariance of the Lagrangian while giving masses to the gauge bosons? This can be accomplished, as first shown in this context by Weinberg and by Salam (*38*), through the device of spontaneous symmetry breaking, which is known as the Higgs mechanism (*39*). Strictly speaking, the gauge symmetry is not so much broken as it is hidden. As before, the gauge fields acquire masses by virtue of their interactions with auxiliary scalar fields. These interactions are manifestly gauge-invariant, as are the self-interactions of the scalar fields. However, the self-interactions of the scalar fields are contrived to make the lowest energy (vacuum) state correspond to a nonzero value of the scalar fields. This is tantamount to the selection of a preferred direction in the internal symmetry space, and so conceals the local gauge symmetry. It was shown by 't Hooft in 1971 (*40*) that the resulting theory is renormalizable, and hence calculable in the same sense as QED. This observation stimulated widespread interest in the predictions of the theory.

In the specific realization chosen by Weinberg and Salam, this procedure leads to the prediction that the charged intermediate boson mass is given by

$$M_W = \left(\frac{\pi\alpha}{G_F\sqrt{2}}\right)^{1/2} \frac{1}{\sin\theta_W} \simeq \frac{37.3\ \mathrm{GeV}/c^2}{\sin\theta_W}$$

where the weak angle θ_W is the parameter that expresses the mixing of B^0 and W^0 to produce the photon and Z^0. The weak angle also characterizes the structure of the weak neutral current in terms of the (third component of) isospin current and the electromagnetic current. It is from the study of neutral current processes that our current knowledge of the weak angle is derived. Finally, in the Weinberg-Salam model, the mass of the neutral intermediate boson is predicted to be

$$M_Z = M_W/\cos\theta_W \geq M_W$$

Intermediate Boson Properties

In recent years, prodigious efforts have been concentrated on studies of the newly discovered neutral current interactions. Taken together, these studies make possible a (nearly) model-independent determination of the properties of the neutral weak current (*41*) which is in striking agreement with the predictions of the Weinberg-Salam model outlined above. Existing experiments determine the weak mixing angle as $\sin^2\theta_W = 0.23 \pm 0.02$. Within the framework of the Weinberg-Salam model, this implies that the intermediate boson masses are $M_W = 78 \pm 5\ \mathrm{GeV}/c^2$ and $M_Z = 89 \pm 5\ \mathrm{GeV}/c^2$. These precise predictions for the intermediate boson masses make inviting targets for the next generation of particle accelerators.

We have already seen that the rate for the leptonic decays $W \rightarrow e\nu$ and so on is fixed by the low-energy phenomenology and the W-boson mass. The quark model of strongly interacting particles makes possible an estimate of the nonleptonic decay rate as well. Assuming that there are N weak doublets of quarks (which occur in three distinguishable "colors") and leptons into which the W can decay, we expect that the total width of the charged IVB is $\Gamma(W^\pm \rightarrow \mathrm{all}) \approx 4N \times 0.2$ GeV. On present evidence the number of quark and lepton doublets is (no less than) three, so we estimate $\Gamma(W^\pm \rightarrow \mathrm{all}) \approx 2.5$ GeV, which corresponds to the lifetime $\tau_W \simeq 2.6 \times 10^{-25}$ second. The intermediate boson is indeed ephemeral, and would be even more so if more species of decay products should exist. The fraction of W decays into $e\nu$ or $\mu\nu$, which are favorable modes from the point of view of detection, is simply

$$B(W \rightarrow e\nu) = B(W \rightarrow \mu\nu) = 1/4N$$

which is approximately 8 percent for three generations.

The scale of decays of the neutral intermediate boson Z^0 is set by the unobservable decay modes $Z^0 \rightarrow \nu_i\bar{\nu}_i$, which entail neutral current couplings independent of the weak angle. These occur at the rate

$$\Gamma(Z^0 \rightarrow \nu_i\,\bar{\nu}_i) \simeq G_F M_Z^3/12\pi\sqrt{2}$$

$$\simeq 3.32 \times 10^{17}\left(\frac{M_Z}{1\ \mathrm{GeV}/c^2}\right)^3 \mathrm{sec}^{-1}$$

The decays of Z^0 into a pair of charged leptons, which may be the best experimental signature, depend on the weak angle. For $\sin^2\theta_W = 0.23$, the expected rate is $\Gamma(Z^0 \rightarrow \ell^+\ell^-) \simeq \frac{1}{2}\Gamma(Z^0 \rightarrow \nu\bar{\nu})$. The total width is approximately $\Gamma(Z^0 \rightarrow \mathrm{all}) = 5.5 \times N \times \Gamma(Z^0 \rightarrow \nu\bar{\nu}) \simeq 2.5$ GeV for $N = 3$. The branching ratio for decay into charged lepton pairs is given by $B(Z^0 \rightarrow \ell^+\ell^-) \simeq (9/N)$ percent $\simeq 3$ percent.

These gross properties of the IVB's, together with the characteristics of production and decay angular distributions that are also specified by the "standard model" of the weak and electromagnetic interactions, determine the observability of intermediate bosons. We next turn to the specifics of projected experiments.

Future Searches

Experimental facilities now being contemplated and developed hold the promise of testing current ideas about the nature of intermediate bosons. The most decisive result would, of course, be the direct observation of IVB's, which may be accomplished by a number of reactions at high energies.

Colliding beams of antiprotons and protons are expected to operate in the early 1980's at CERN (CM energy of 540 GeV) and at Fermilab (CM energy of 2000 GeV) with luminosities of 10^{30} cm^{-2} sec^{-1}. Later in the decade, the Isabelle project at Brookhaven National Laboratory is to provide 800-GeV collisions of protons on protons with a luminosity exceeding 10^{32} cm^{-2} sec^{-1} (*42*). Extensive predictions for the production and decay of IVB's have been presented by many authors (*43*). The conventional wisdom projects that IVB's will be produced at the rate of tens per hour at the modest-luminosity machines and perhaps thousands per hour at Isabelle. The detection of intermediate boson decays and the separation of signal from background pose interesting challenges for apparatus design. It appears that the leptonic decay modes $W \rightarrow e\nu$, $\mu\nu$ and $Z \rightarrow e^+e^-$, $\mu^+\mu^-$ hold the greatest promise for clean detection, in spite of the small probabilities for these decays. The signature for the Z^0 is the observation of a lepton and antilepton with large (and opposite) momenta at large angles to the beam direction. By measuring the lepton momenta, one may reconstruct the mass of the Z^0. The signature for the $W^\pm$ is the observation of a charged lepton with large transverse momentum that appears not to be balanced by other, oppositely directed particles. Because momentum conservation is well established, it is inferred that the compensating transverse momentum is carried by an undetected neutrino. With one of the decay products undetected, it is impossible to reconstruct the W-boson mass. However, to the extent that the IVB's are produced with modest transverse momenta themselves, the end point of the lepton's transverse momentum spectrum is given by $M_W/2$.

The construction of electron-proton colliding beams at CM energies of several hundred GeV would make accessible a wide range of new physics, including incisive studies of proton structure (*44*). However, the tiny cross sections ($\lesssim 10^{-37}$ cm^2) expected for the reactions $e^- + p \rightarrow e^- + Z^0 +$ anything or $e^- + p \rightarrow \nu_e + W^- +$ anything discourage the search for intermediate bosons in electron-proton collisions.

Much more appealing is the prospect of forming the neutral intermediate boson in electron-positron collisions (*45*). The visible cross section at the Z^0 peak is given by

$$\sigma_{vis}(e^+e^- \rightarrow Z^0) = (9/\alpha^2)B(Z^0 \rightarrow e^+e^-)$$

$$\times\ B(Z^0 \rightarrow \text{visible}) \times \sigma(e^+e^- \rightarrow \mu^+\mu^-)$$

$$\simeq \frac{12{,}750}{N}\,\sigma(e^+e^- \rightarrow \mu^+\mu^-)$$

where the branching ratio for visible decays (excluding $Z^0 \rightarrow \nu\bar{\nu}$) is approximately 9/11 for any number N of quark and lepton doublets and the pointlike reference cross section $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ is evaluated at the Z^0 mass. For the three generations indicated by current experiments, a fantastic rate of 4250 times the pointlike cross section is expected. A luminosity of 10^{32} cm^{-2} sec^{-1} would then imply the detection of several Z^0's per second. In addition to demonstrating the existence of the neutral intermediate boson, a Z^0 factory would provide a copious source of all the particles into which the Z^0 can decay. Within the Weinberg-Salam framework, precise measurements of the Z^0 width and the peak cross section would yield a count of the number of neutrino species and would bound the total number of light fermion species. At sufficiently high energies, e^+e^- annihilations may lead to the production of W^+W^- pairs. Study of the energy dependence of $\sigma(e^+e^- \rightarrow W^+W^-)$ may test the gauge-invariant structure of the theory.

Before new accelerators make possible the direct observation of IVB's, it is unlikely (in view of our theoretical biases) that propagator effects might become detectable. The extension of νN total cross section (and related) measurements to significantly higher energies, which will follow the commissioning of the superconducting Tevatron at Fermilab, will only begin to provide sensitivity to W-boson masses in the expected range. Similarly, observations of the forward-backward asymmetry in the reaction $e^+e^- \rightarrow \mu^+\mu^-$ at CM energies approaching 40 GeV will further refine our knowledge of the Z^0 couplings to leptons, but are relatively insensitive to the Z^0 mass. Of course, we reserve the right to be surprised.

Consequences of the Searches

Discovery of the intermediate bosons $W^\pm$ and Z^0 at their predicted masses would be of extreme importance for the following reasons. (i) It would represent the first direct confirmation of the idea of unification of weak and electromagnetic interactions. (ii) It would make possible the precise measurement of the mixing parameter $\sin^2\theta_W$. Accurate knowledge of $\sin^2\theta_W$ can have important consequences for "grand unified" theories that seek to unify the strong, weak, and electromagnetic interactions. Various grand unified theories embody specific predictions for $\sin^2\theta_W$. (iii) Study of the decay modes of the IVB's may reveal hitherto unknown flavors of quarks and leptons.

A word of caution is nevertheless in order. Discovery of the IVB's at their predicted masses would by no means demonstrate the correctness of the idea of spontaneously broken gauge theories in which the Higgs mechanism plays an essential role. It would merely confirm the idea of electroweak unification. In the framework of broken $SU(2) \otimes U(1)$ symmetry, the masses of $W^\pm$ and Z^0 may take on the canonical values, whether the Higgs mechanism is realized through the action of auxiliary fields which are elementary (à la Weinberg-Salam) or composite ("dynamical symmetry breaking"). The mechanism of symmetry breaking thus remains to be investigated, even if the IVB's appear as predicted.

What would be the significance of not finding the IVB's at the canonical masses? Several possibilities may be contemplated; we summarize the simplest of these.

1) The intermediate bosons are not found at all. Bjorken (*46*) has shown that the success of the standard model in explaining the low-energy charged current and neutral current phenomenology can be emulated by assuming a global SU(2) symmetry as proposed by Bludman, provided all fermions have a large charge radius. Such a description is, of course, not renormalizable.

2) The intermediate bosons exist, but with masses very different from the canonical values. One realization is a model due to Hung and Sakurai (*47*), motivated by Bjorken's approach. This picture is based on the assumption of a global SU(2) symmetry and ad hoc mixing between W^0 and the photon. Again, the low-energy phenomenology is faithfully reproduced. However, the only constraint in general (*48*) is $M_W \lesssim 160$ GeV/c^2.

3) The $W^\pm$ bosons are discovered at the canonical mass, but the Z^0 is found at a nonstandard mass. This may be taken as an indication that the electroweak gauge group is not simply $SU(2) \otimes U(1)$,

but a larger group for which there will be many neutral gauge bosons. There might be additional charged bosons as well, but these must be at least three times as massive as the standard W boson to preserve the successful low-energy phenomenology.

The definiteness of present expectations for intermediate boson properties and the prospect that meaningful searches are close at hand make for exciting times ahead. We may look forward to the dramatic confirmation or the drastic revision of current ideas about the unification of fundamental forces. The outcome of the search for intermediate bosons is thus likely to have implications that range far beyond the weak and electromagnetic interactions alone.

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